Enhanced Condensation for Organic Rankine Cycle

7th Quarterly Progress Report

Reporting Period: July 1, 2014 – Sept 30, 2014

Project Grantor: **Alaska Energy Authority**
Alan Baldivieso, Program Manager
813 W. Northern Lights Blvd. AK 99503
907-771-3027 (voice), Email: abaldivieso@aidea.org

Project Grantee: University of Alaska, Institute of the Northern Engineering
Maggie Griscavage
P.O. Box 757880, Fairbanks, AK 99775
907-474-7301 (voice), Email: fygrcon@uaf.edu\

Grant Agreement Number: 7310028
Project Code: 413006

Principal Investigators: **Sunwoo Kim**, PhD (PI)
Mechanical Engineering Department
University of Alaska, Fairbanks
907-474-6096 (voice), Email: swkim@alaska.edu

1. Back Ground

Generating electricity from low grade heat sources has attracted attention due to rising fuel price and increasing energy demand. The organic Rankine cycle (ORC) system is the most practical solution among technologies developed for low grade heat recovery. However, the efficiency of a typical small scale ORC is 10% or less. Most energy loss in the ORC is attributed to thermodynamically irreversible heat transfer processes occurring in its heat exchangers: the evaporator and condenser. In particular for waste heat recovery ORCs, economical success is mainly determined by effectiveness of the condenser because, while their heat source is provided at no cost, heat rejection accounts for most of operation cost. Almost half of total cost for operation and maintenance of an ORC system can stem from its condenser. We investigate and demonstrate heterogeneous condensing surfaces that potentially reduce the irreversibility during the condensation of organic fluids.

2. Progress Report

We have made progress during the reporting period (July 1 – September 30, 2014) and progress activities are described below.

Task 1: Model Development (Completed)

Task 2: Design and Construction of Testing Apparatus (Completed)

The designed condensation testing apparatus has been constructed. Regular maintenance is being continuously conducted. It includes calibration of sensors, replacement of o-rings, reapplication of sealant, and leaking test. As we found leakages from joints, o-rings, and/or valves in September, a thorough investigation has been carried out to find and fix the sources of leakage. The test results reported in the document were collected before the testing apparatus allowed leakage.

Task 4: Optimization of design parameters

During the reporting period we experimentally evaluated the performance of a heterogeneous condensing surface for different orientations: horizontal and vertical. Figure 1 illustrates the horizontal and vertical samples, where the dark and bright stripes represent the hydrophobic coating and copper substrate, respectively. Details on the heterogeneous condensing surface samples can be found in the previous reports.

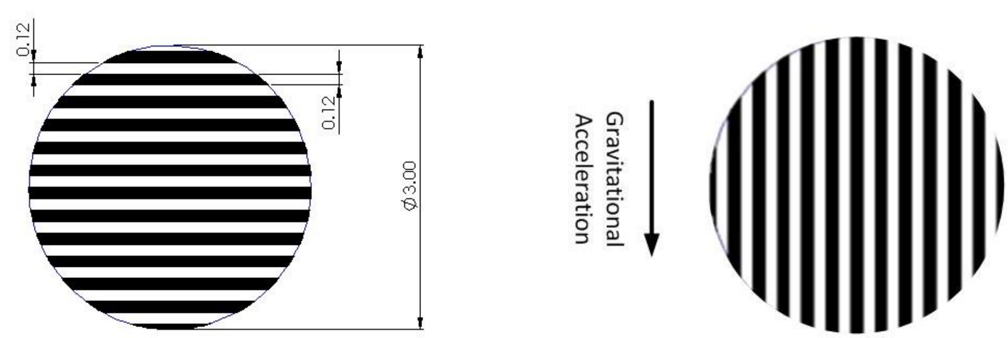

Figure 1: Horizontal (left) and vertical (right) orientation of heterogeneous condensing surface samples

The difference between the horizontal and the vertical heterogeneous samples is only the angle of the stripes with respect to the direction of gravitational acceleration. Nonetheless, it behaved differently. The drop departure on the hydrophobic stripe was similar to that of the horizontal case, but the drop departure on the hydrophilic stripe was hardly witnessed on vertically oriented samples.

Heat transfer rate per unit area

Figure 2 shows the experimental heat transfer rate per unit condensing area, which is also called the heat flux. It is obvious that the horizontal heterogeneous sample transferred as much heat as the fully hydrophobic sample, which is plotted with the steeper dotted straight line in the figure. Below subcooling temperature of 3 K the heat flux for the horizontal heterogeneous surface was found nearly identical to the hydrophobic-treated copper sample. This was undoubtedly due to the same degree of bare surface area. At lower subcooling temperatures, the area of bare surface that was exposed to the vapor was the same in both cases. As the subcooling temperature increased (> 3 K), the drops began to fall off the surface. The drops from the hydrophobic stripes swept away the drops on the hydrophilic stripes, except for the drops of the first few stripes on the top half that were unable to be swept away. Thus, the resistance created by the drops that were unable to be swept away became substantial, resulting in a higher thermal resistance. After the subcooling temperature of 3 K, the heat flux for the horizontal heterogeneous sample started generating discrepancy from the hydrophobic sample.

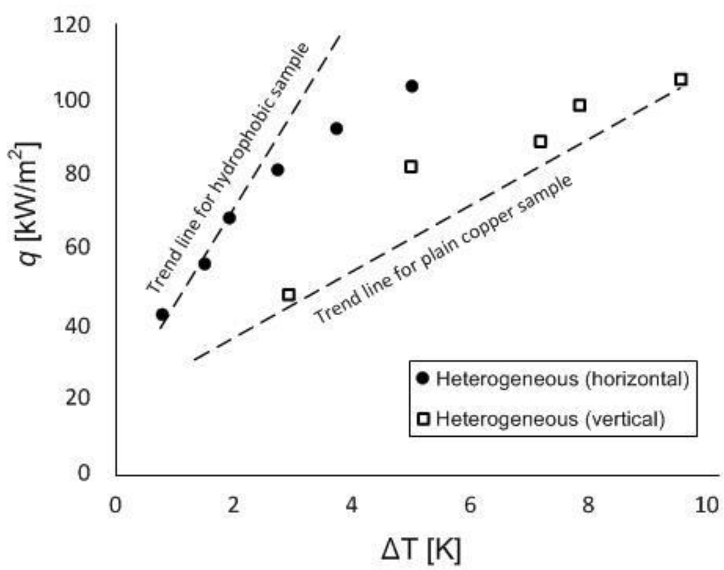

Figure 2: Heat flux for heterogeneous samples in comparison with full-hydrophobic and non-treated samples

The experimental results of heat transfer coefficient for the heterogeneous surfaces in Fig. 3 also demonstrate that the horizontally aligned sample effectively reduces thermal resistance at low subcooling temperatures and that the vertical sample is outperformed by the horizontal one. When the vertical heterogeneous sample is compared with the plain sample, the heat transfer coefficient at ΔT = 4 ~ 5 K was 16 and 12 kW/m^2-K for the vertical and plain sample, respectively. At ΔT = 8 K it was 12.5 and 11 kW/m^2-K for the vertical and plain sample, respectively. The greater heat transfer coefficients compared to the plain copper sample are due to the easy departure of drops on the hydrophobic stripes.

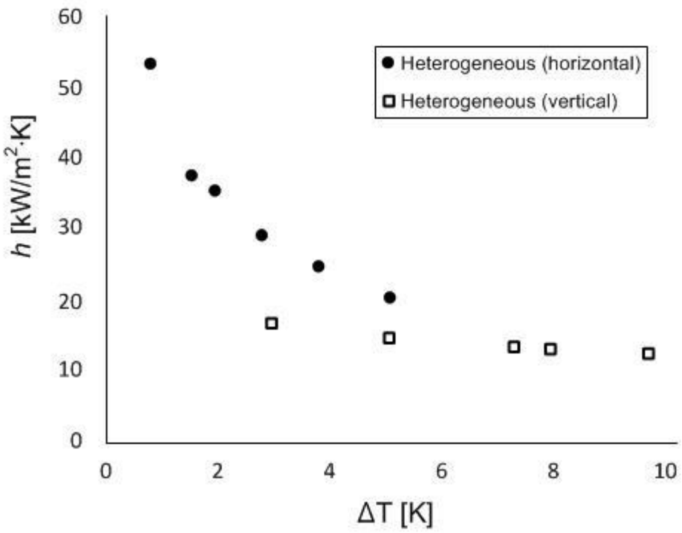

Figure 3: Heat transfer coefficient for heterogeneous samples in comparison with full-hydrophobic and non-treated samples

Until now experimental investigation has been conducted for a plain copper sample, fully hydrophobic-treated copper sample, and heterogeneous samples in a flat plate condenser. The heterogeneous surface has been tested for the first time to investigate the heat transfer coefficients and drop formation behavior on it. From the observations and measured results the following conclusions were drawn.

1. Condensation heat transfer of steam on the hydrophobic-treated sample is superior to that on the plain copper surface despite the fact that both the surfaces stably promote dropwise condensation, even though visually examined contact angles are almost identical on the both surfaces. This is attributed to the size of the droplets that are about to depart. The difference in the droplets behavior is due to the surface free energy difference between the samples. The lower surface free energy causes low wettability of the droplet, reducing the size of departing droplets.

2. The heat transfer coefficients for the horizontal heterogeneous surface at lower subcooling temperatures are as high as the heat transfer coefficients for the homogeneous hydrophobic-treated surface. This is because the drops generated on the non-treated stripes are carried away by drops from the hydrophobic stripes due to the orientation of the horizontal heterogeneous surface. The heat transfer coefficients decrease with increase in the subcooling temperatures. This is partially attributed to the drops which are unable to be swept away on the top part of the condensing surface.

3. The heat transfer coefficient for the vertical heterogeneous sample at $\Delta T = 4$ K is about 25% greater than that of the plain sample. The enhancement of the horizontal heterogeneous sample over the plain sample is approximately 100%. The enhancement is not comparable to that of the horizontal heterogeneous surface, because of the orientation of the sample. The drops generated on the hydrophobic stripes do not have any influence on the drops on the hydrophilic stripes due to the orientation. Thus, less enhancement in the heat transfer coefficients are obtained.

4. Higher heat transfer coefficients are observed at lower subcooling temperatures for all the samples. This is due to the number of drops covering the condensing surface. At lower at

subcooling temperatures the drop generation is slow and thus the bare surface area of the condensing surface exposed to the vapor. The lower drop generation at lower subcooling temperatures results in higher heat transfer coefficients.